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**Finding the Leptonic  $WW$  Decay Mode  
of a Heavy Higgs Boson  
at Hadron Supercolliders**

V. Barger,<sup>1</sup> Kingman Cheung,<sup>2</sup> T. Han,<sup>3</sup> D. Zeppenfeld<sup>1</sup>

<sup>1</sup>*Department of Physics, University of Wisconsin, Madison, WI 53706*

<sup>2</sup>*Department of Physics & Astronomy, Northwestern University, Evanston IL 60208*

<sup>3</sup>*Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, IL 60510*

**ABSTRACT**

We reanalyze the extraction of the heavy Higgs boson signal  $H \rightarrow W^+W^- \rightarrow \bar{\ell}\nu, \ell\bar{\nu}$  ( $\ell = e$  or  $\mu$ ) from the Standard Model background at hadron supercolliders, taking into account revised estimates of the top quark background. With new acceptance criteria the detection of the signal remains viable. Requiring a forward jet-tag, a central jet-veto, and a large relative transverse momentum of the two charged leptons yields  $S/\sqrt{B} > 6$  for one year of running at the SSC or LHC.

One of the most important physics issues at hadron supercolliders is the identification of a heavy Higgs boson in its various production and decay channels. Single forward jet-tagging (FJT) has been shown to be very effective in separating the weak boson scattering contribution from the gluon fusion process and the QCD backgrounds in the case of  $H \rightarrow ZZ \rightarrow 4\ell$  [1]. This separation of production mechanisms is important to fully probe the heavy Higgs sector. Similarly, it is desirable to independently identify the  $H \rightarrow ZZ$  and  $H \rightarrow WW$  decay modes, in order to test the custodial  $SU(2)$  symmetry. Moreover, a neutral techni-rho  $\rho_{TC}^0$  would dominantly decay to  $W^+W^-$  rather than  $ZZ$ .

Recently, the present authors proposed a method for separation of the leptonic  $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$  signal from the large QCD and top-quark pair production backgrounds [2]. The technique relied on the tagging of a single forward jet to single out the weak boson scattering process, and the imposition of a central jet-veto (CJV) to suppress the remaining contribution from top quark pair-production in association with a QCD jet (denoted by  $t\bar{t}j$ ), where the  $b$ -jets from the top-quark decays populate the central rapidity region.

Subsequent to our work, shower Monte Carlo studies for jet-tagging were made of the signal and the backgrounds in the  $WW$  fusion channel [3]. Agreement was found with our calculation except for the amount of  $t\bar{t}j$  background suppression, with the shower Monte Carlo results finding substantially larger top backgrounds. This disagreement prompted us to reexamine our calculation for this channel. We have now identified the source of the disagreement as a mis-assigned distribution in the output of our computer code: the energy distribution of the tagging jet in the  $t\bar{t}j$  background was assigned in the parton center of mass frame rather than the laboratory frame. Since the two distributions are very different, the  $t\bar{t}j$  background is found to be higher than originally calculated [2]. Therefore it is necessary for us to reevaluate the viability of the  $H \rightarrow W^+W^-$  signal identification above backgrounds. Fortunately, we find a positive conclusion, provided that the relative transverse momentum of the leptons is required to be large and that the jet-veto requirement is tightened. Results of our revised analysis are

given below. Apart from the correction in the computer code the analysis closely parallels that used by us previously [2].

The leptons arising from the decay of a heavy Higgs boson typically carry large transverse momenta and they populate the central rapidity region. As in our original analysis we require

$$p_{T\ell} > 100 \text{ GeV and } |y_\ell| < 2, \quad (1)$$

throughout. A central feature of our analysis is the tagging of one of the forward quark-jets arising in the  $q_1 q_2 \rightarrow q_3 q_4 W^+ W^-$  signal. Figure 1 compares the differential  $d^2\sigma/dE_j d|\eta_j|$  distribution in absolute value of pseudorapidity  $|\eta_j|$  versus the energy  $E_j$  of the tagged jet for the signal ( $m_H = 1 \text{ TeV}$ ) and the  $t\bar{t}j$  background. By selecting a region of high rapidities and substantial tagging jet energies,

$$3 < |\eta_j(\text{tag})| < 5, \quad E_j(\text{tag}) > 1 \text{ TeV}, \quad \text{and} \quad p_{Tj}(\text{tag}) > 40 \text{ GeV}, \quad (2)$$

the backgrounds with QCD jet emission are suppressed relative to the signal. The benefits of a more stringent jet-tagging requirement will be discussed later.

The effectiveness of a central jet-veto is demonstrated in Fig. 2 which shows the pseudorapidity distribution of the second jet (veto candidate). While the signal events rarely produce a central jet with  $p_{Tj} > 30 \text{ GeV}$ , the rate of such jets in the  $t\bar{t}j$  background is quite large. We tighten the central jet-veto cut of Ref. [2], and reject events with

$$p_{Tj}(\text{veto}) > 30 \text{ GeV}, \quad |\eta_j(\text{veto})| < 3, \quad (3)$$

which is still above the 25 GeV central-jet threshold used by the SDC Collaboration [3]. Eq.(3) will be the central jet-veto (CJV) requirements for background suppression. The combined efficiency of the FJT and CJV for a 1 TeV Higgs-boson signal is about 40%, while these cuts reduce the  $t\bar{t}j$  background by about 3 orders of magnitude.

The charged leptons originating from the heavy Higgs-boson signal have higher  $p_T$  (typically  $m_H/4$ ) and are more back-to-back than the backgrounds [4–6]. We find that the distribution in

$$\Delta p_{T\ell} = |p_{T\ell_1} - p_{T\ell_2}|, \quad (4)$$

which has been considered previously in studying  $W^+W^+ \rightarrow W^+W^+$  scattering [5], is an appropriate vehicle to reduce the  $t\bar{t}j$  background to acceptable levels. The  $\Delta p_{T\ell}$  distributions for the signal and the various background processes at the SSC energy are shown in Fig. 3. By requiring

$$\Delta p_{T\ell} > 400 \text{ GeV} \quad (5)$$

we obtain a sufficient suppression of  $t\bar{t}j$  events.

We summarize the effects of the acceptance cuts in two tables, for the SSC and LHC, respectively. The first line in Tables I and II gives the cross sections (in fb) for the 1 TeV and 0.6 TeV Higgs-boson cases, the electroweak transverse  $W$  background (estimated with the  $m_H = 0.1$  TeV SM expectation), the QCD background, the  $t\bar{t}j$  background (for  $m_t = 140$  and 180 GeV), and the significance  $S/\sqrt{B}$  of the  $m_H = 1$  TeV signal estimated with  $m_t = 140$  GeV and an integrated luminosity of  $10 \text{ fb}^{-1}$  ( $100 \text{ fb}^{-1}$ ) at the SSC (LHC). Thus a high level of significance can be achieved, even if uncertainties in background normalization are folded in.

Beyond the acceptance criteria used above, the kinematic distributions of the heavy Higgs signal and the backgrounds differ substantially. As examples Fig. 4 gives the energy distribution of the tagged jet at the SSC and the LHC, Fig. 5 shows the distributions in  $p_{T\ell}^{\max}$  of the lepton with the maximal transverse momentum, and Fig. 6 gives the distribution in  $m_{\ell j}^{\min}$  of the smaller of the two lepton-tagging jet invariant masses. In all three examples the distribution of the signal is much flatter than that of the major backgrounds.

Because the signal and background distributions are quite different in shape, the positive identification of a Higgs signal is independent of modest normalization uncertainties in the prediction of the signal and background cross sections. A simultaneous fit to the shape of all the available distributions is the most promising means for an unambiguous extraction of the heavy Higgs signal. Short of such a complete analysis, one can improve the significance of the signal by more stringent acceptance criteria, at modest cost to the signal rate. The last few lines in the

two tables provide illustrations. Although the large  $\Delta p_{T\ell}$  criterion seems to be most effective, large  $p_{T\ell}^{\max}$  is useful too. Cuts on the  $m_{\ell j}^{\min}$  variable [5] appear promising as well, the uncertainties on the energy and direction of the tagging jet may mitigate its usefulness, however.

Our analysis was largely based on an assumed top mass of 140 GeV. The suppression of the top background is easier for heavier  $m_t$  because  $b$  quarks from the top decay have higher  $p_T$  and the central jet-veto is more effective. This is illustrated in Tables I and II by the  $m_t = 180$  GeV columns: the dominant top quark background is reduced by a factor 1.5.

In addition to the forward jet-tagging and the central jet-vetoing, the  $\Delta p_{T\ell} > 400$  GeV cut is crucial for the top quark background reduction. This cut is specifically tailored for the case of a 1 TeV Higgs. As can be seen from the tables, this cut starts to be too severe for Higgs masses around or below 0.6 TeV. For such Higgs masses a relaxed  $\Delta p_{T\ell}$  cut combined with a more stringent cut on the tagging jet energy  $E_j(\text{tag})$  would be desirable, as can be deduced from the effects of increasing these cuts in Tables I and II for the  $m_H = 600$  GeV case.

We conclude that the prospects for finding the  $WW$  leptonic decays of the heavy Higgs boson at the LHC or SSC remain very good, in spite of the fact that the  $t\bar{t}j$  background is larger than previously indicated. We have found improved selection criteria which make an effective background suppression still possible. In addition to the forward jet-tag and central jet-veto a substantial relative  $p_T$  of the two leptons must be demanded.

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## REFERENCES

- [1] V. Barger, K. Cheung, T. Han, J. Ohnemus, and D. Zeppenfeld, Phys. Rev. **D44**, 1426 (1991).
- [2] V. Barger, K. Cheung, T. Han, and D. Zeppenfeld, Phys. Rev. **D44**, 2701 (1991).
- [3] SDC Technical Design Report, SDC-92-201 (1992); K. Einsweiler (private communication).
- [4] V. Barger, K. Cheung, T. Han, and R. J. N. Phillips, Phys. Rev. **D42**, 3052 (1990).
- [5] D. Dicus, J. F. Gunion, and R. Vega, Phys. Lett. **B258**, 475 (1991); D. Dicus, J. F. Gunion, L. H. Orr, and R. Vega, Nucl. Phys. **B377**, 31 (1991).
- [6] M. Berger and M. Chanowitz, Phys. Lett. **B263**, 509 (1991).

# TABLES

TABLE I. SSC cross section in fb for various acceptance cuts on  $W^+W^-jX$  events with leptonic  $W$  decays. The tagging requirements ( $E_j(\text{tag}) > 1$  TeV,  $p_{Tj}(\text{tag}) > 40$  GeV, and  $3 < |\eta_j(\text{tag})| < 5$ ), central jet-veto ( $p_{Tj}(\text{veto}) > 30$  GeV and  $|\eta_j(\text{veto})| < 3$ ), and generic lepton cuts ( $p_{Tl} > 100$  GeV,  $\Delta p_{Tl} > 400$  GeV, and  $|y_l| < 2$ ) are imposed throughout. In addition results are shown for a selection of enhanced acceptance cuts. The final column gives the significance  $S/\sqrt{B}$  for  $m_H = 1$  TeV,  $m_t = 140$  GeV, and an integrated luminosity of  $10 \text{ fb}^{-1}$ , corresponding to one year of running at design luminosity.

<u>Further cuts</u>	<u><math>m_H</math> (TeV)</u>			<u>QCD</u>	<u><math>t\bar{t}j</math></u>		<u><math>S/\sqrt{B}</math></u>
	1.0	0.6	0.1		$m_t = 140$	$m_t = 180 \text{ GeV}$	
no additional	5.8	2.5	0.54	0.79	4.3	2.8	7.1
$E_j(\text{tag}) > 1.5 \text{ TeV}$	5.1	2.2	0.49	0.51	2.8	1.8	7.5
$\Delta p_{Tl} > 450 \text{ GeV}$	4.8	1.4	0.42	0.59	2.5	1.5	7.4
$p_{Tl}^{\text{max}} > 270 \text{ GeV}$	5.0	1.6	0.46	0.59	2.6	1.6	7.4
$m_{lj}^{\text{min}} > 500 \text{ GeV}$	5.2	2.2	0.44	0.50	3.0	1.9	7.6

TABLE II. LHC cross section in fb for various acceptance cuts on  $W^+W^-jX$  events with leptonic  $W$  decays. Acceptance cuts are as in Table 1 except for a relaxed tagging requirement  $E_j(\text{tag}) > 0.8$  TeV. The final column gives the significance  $S/\sqrt{B}$  for  $m_H = 1$  TeV,  $m_t = 140$  GeV, and an integrated luminosity of  $100 \text{ fb}^{-1}$ , corresponding to one year of running at design luminosity.

<u>Further cuts</u>	<u><math>m_H</math> (TeV)</u>			<u>QCD</u>	<u><math>t\bar{t}j</math></u>		<u><math>S/\sqrt{B}</math></u>
	1.0	0.6	0.1		$m_t = 140$	$m_t = 180 \text{ GeV}$	
no additional	0.46	0.25	0.044	0.11	0.34	0.21	5.9
$E_j(\text{tag}) > 1.0 \text{ TeV}$	0.42	0.23	0.041	0.078	0.28	0.17	6.0
$E_j(\text{tag}) > 1.2 \text{ TeV}$	0.38	0.21	0.038	0.059	0.23	0.14	6.0
$\Delta p_{Tu} > 450 \text{ GeV}$	0.37	0.13	0.031	0.074	0.17	0.11	6.5
$p_{Tl}^{\text{max}} > 270 \text{ GeV}$	0.37	0.15	0.034	0.067	0.18	0.11	6.3
$m_{lj}^{\text{min}} > 500 \text{ GeV}$	0.38	0.20	0.032	0.054	0.21	0.13	6.4

## FIGURES

FIG. 1.  $d^2\sigma/dE_j d|\eta_j|$  distributions of the tagged jet at the SSC from (a) the  $m_H = 1$  TeV SM signal, and (b) the  $t\bar{t}j$  background for  $m_t = 140$  GeV. The acceptance cut of Eq. (1) are imposed.

FIG. 2. Pseudorapidity distributions of the second jet (veto candidate) for the  $t\bar{t}j$ , electroweak  $qqWW$  ( $m_H = 0.1$  TeV) backgrounds and the  $m_H = 1$  TeV SM Higgs boson signal at the SSC with a tagging jet requirement of  $E_j > 1$  TeV. The acceptance cuts are those of Eqs. (1), (2), and (5) and  $p_{Tj}(\text{veto}) > 30$  GeV.

FIG. 3. Relative transverse momentum distribution  $\Delta p_{T\ell}$  for the signal and the various background processes at the SSC, with the acceptance cuts of Eqs. (1), (2), and (3).

FIG. 4. Energy distribution (a) at the SSC and (b) at the LHC of the tagged jet, with the acceptance cuts of Eqs. (1), (2), (3), and (5).

FIG. 5. Distribution in transverse momentum  $p_{T\ell}^{\text{max}}$  of the charged lepton with the maximum  $p_T$  in each event. Acceptance cuts are as in Fig. 4.

FIG. 6. Distribution in the smallest invariant mass of a charged lepton with the tagging jet. Acceptance cuts are as in Fig. 4.

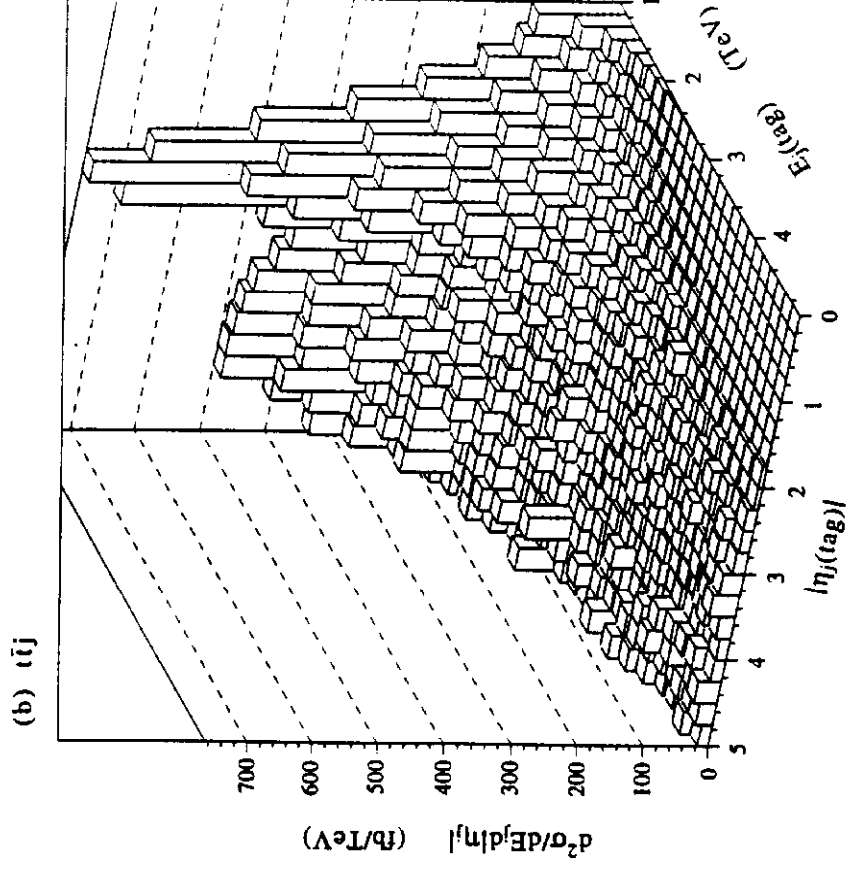
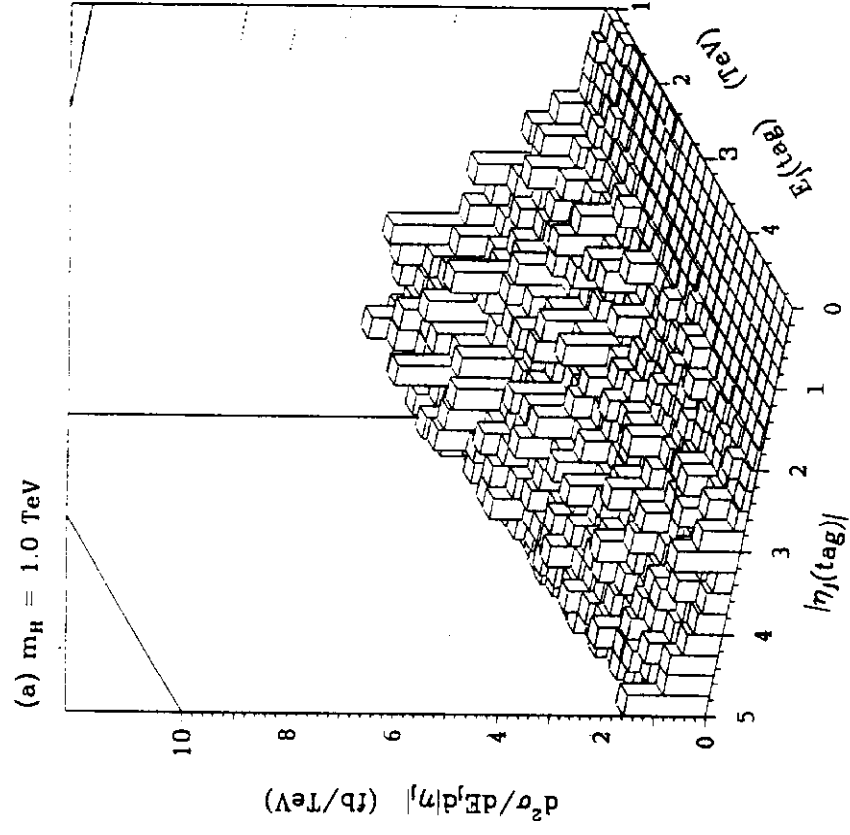


Figure 1

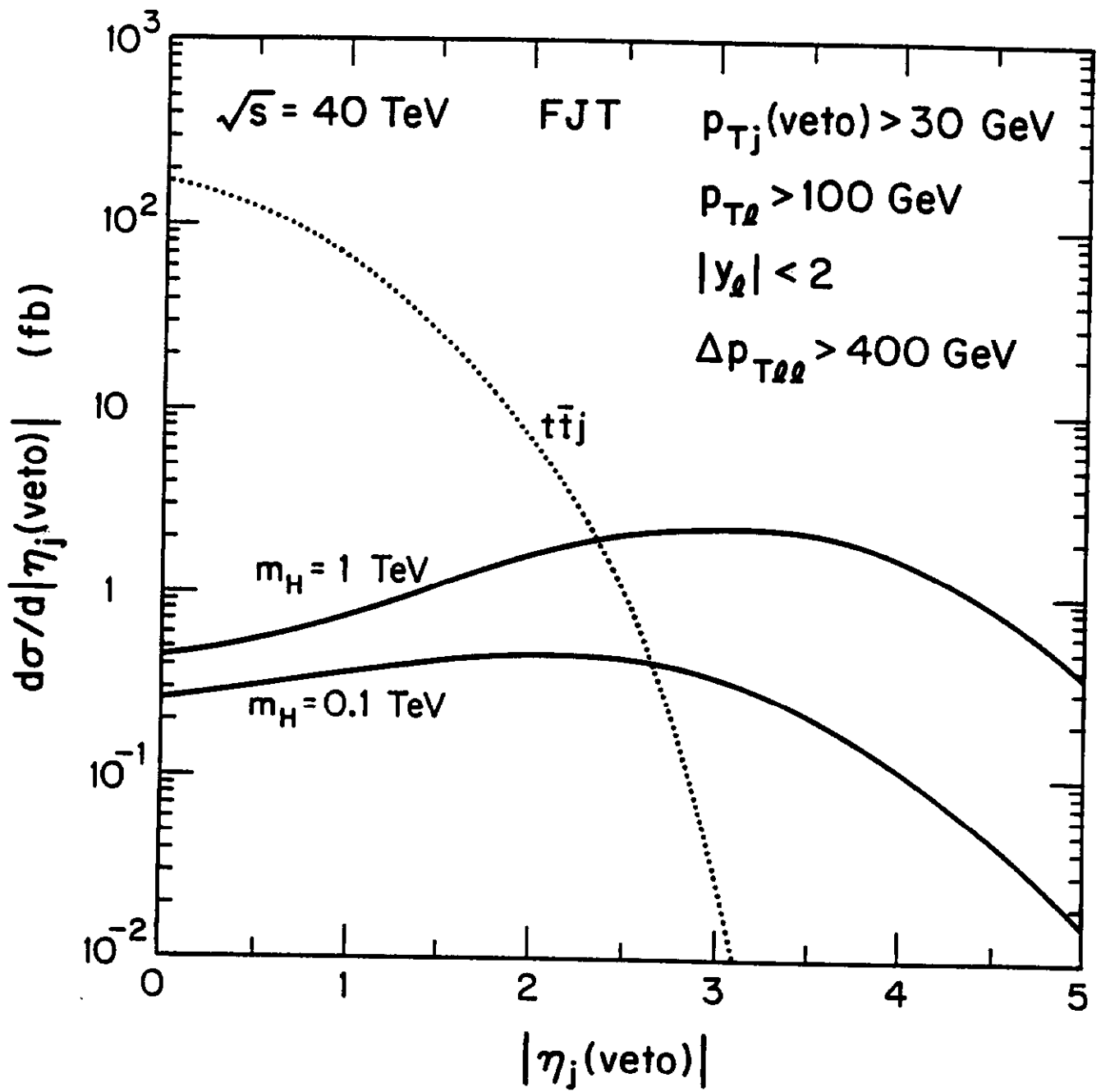


Figure 2

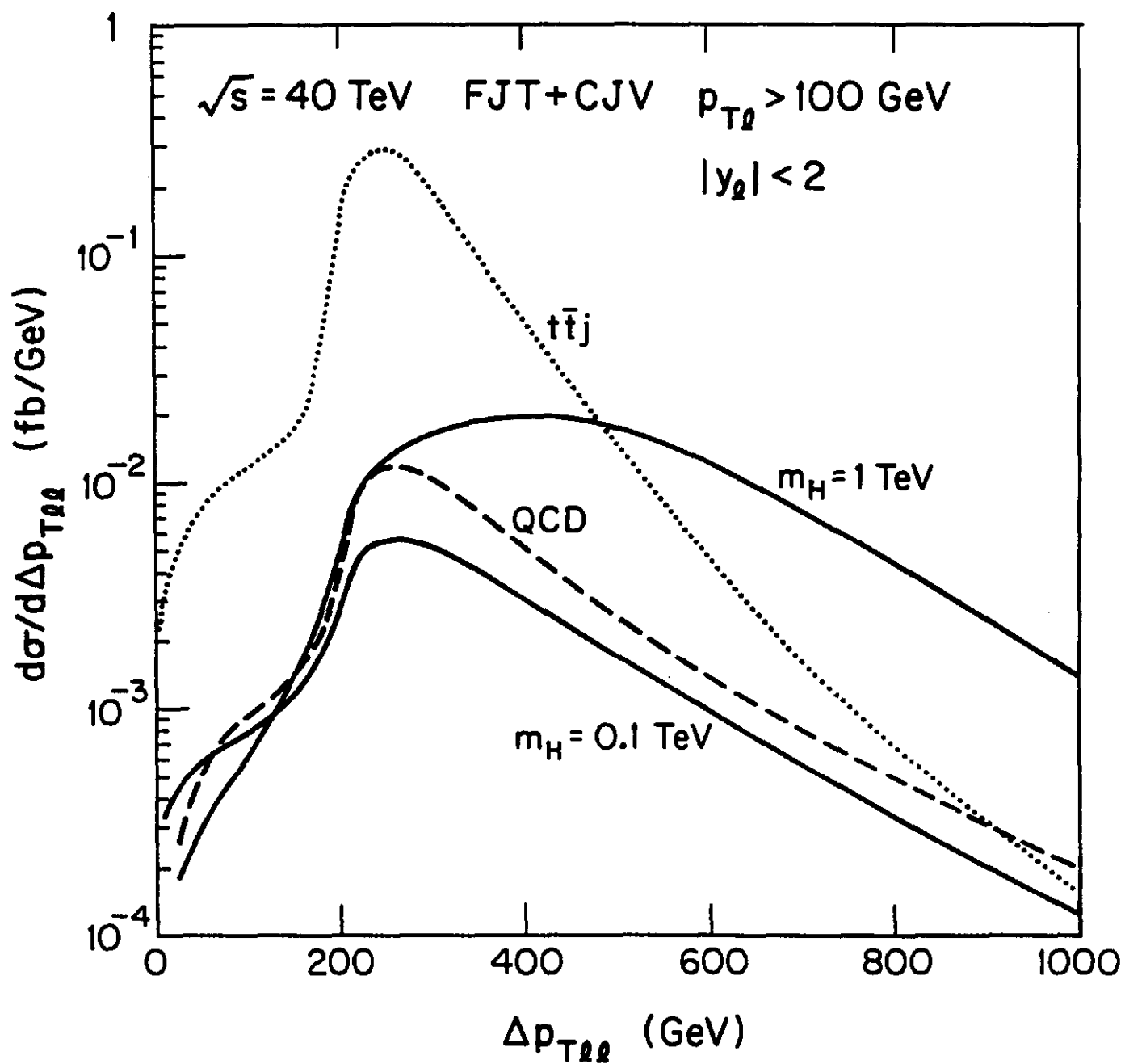


Figure 3

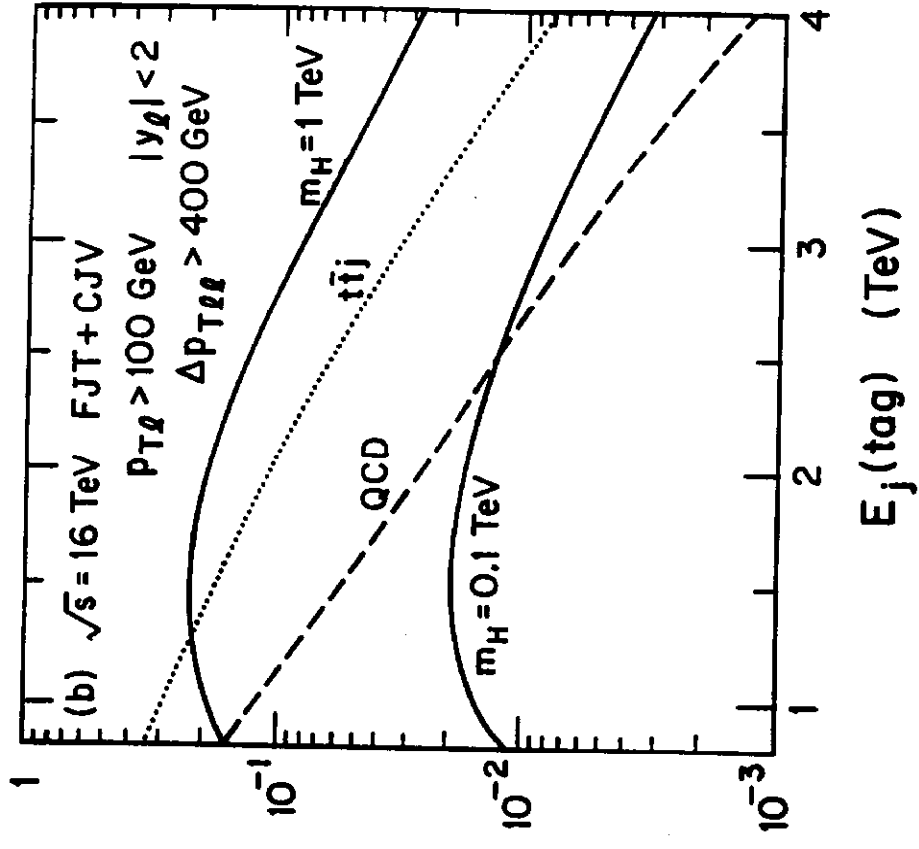
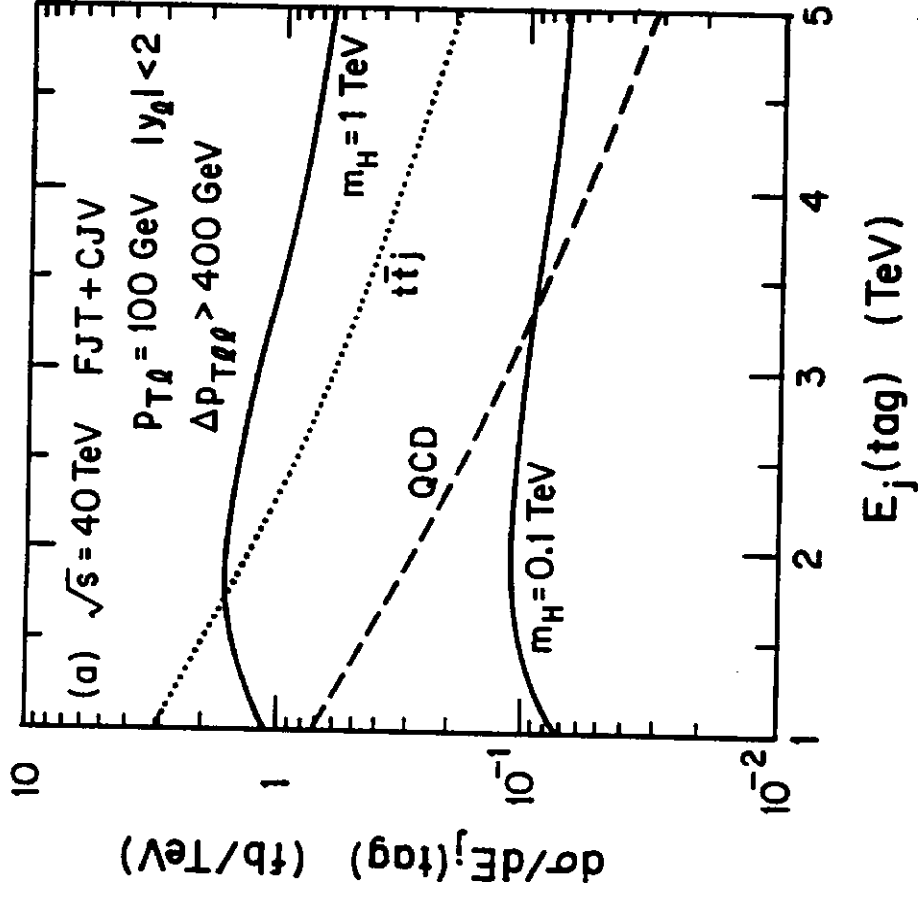


Figure 4

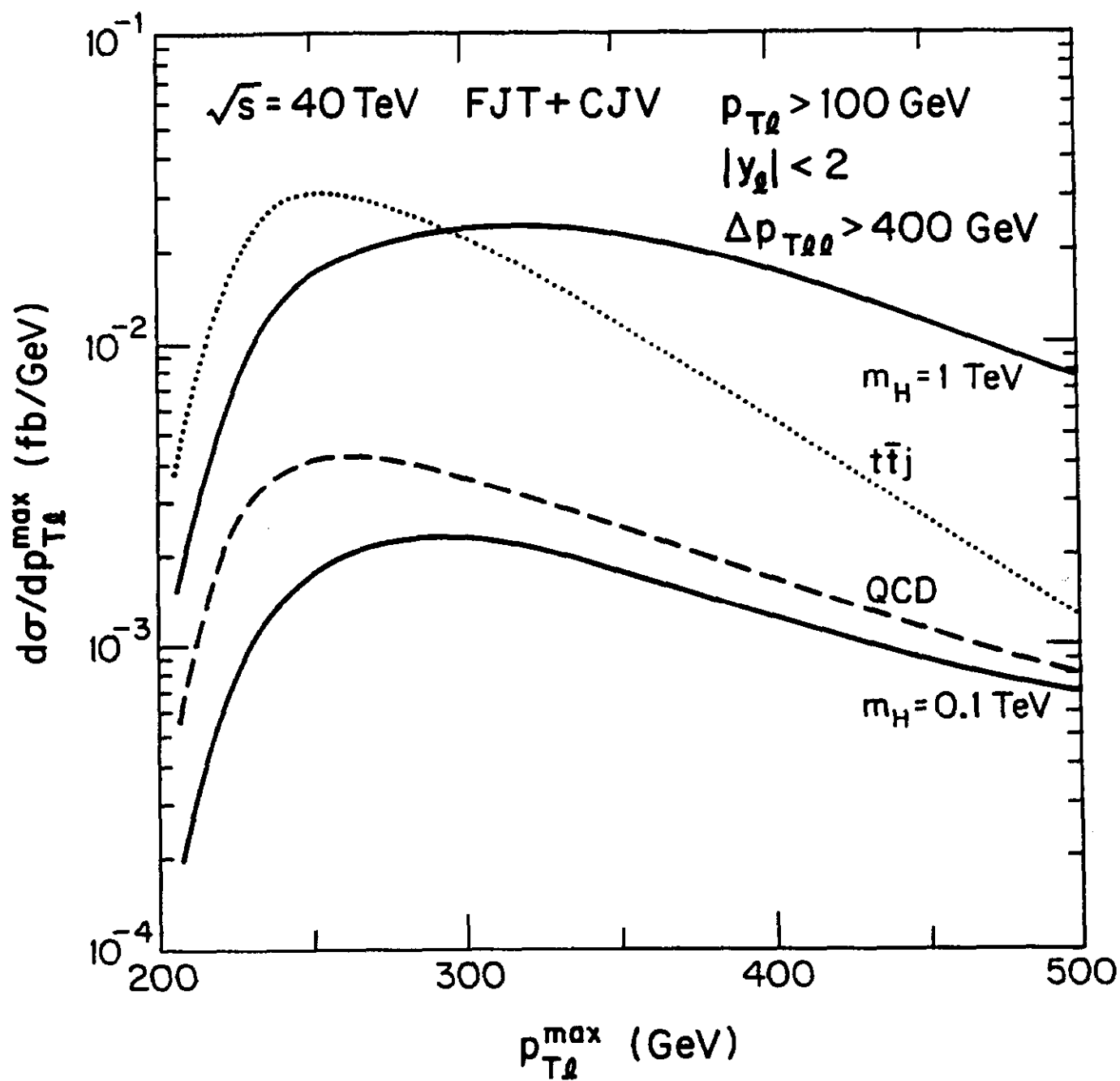


Figure 5

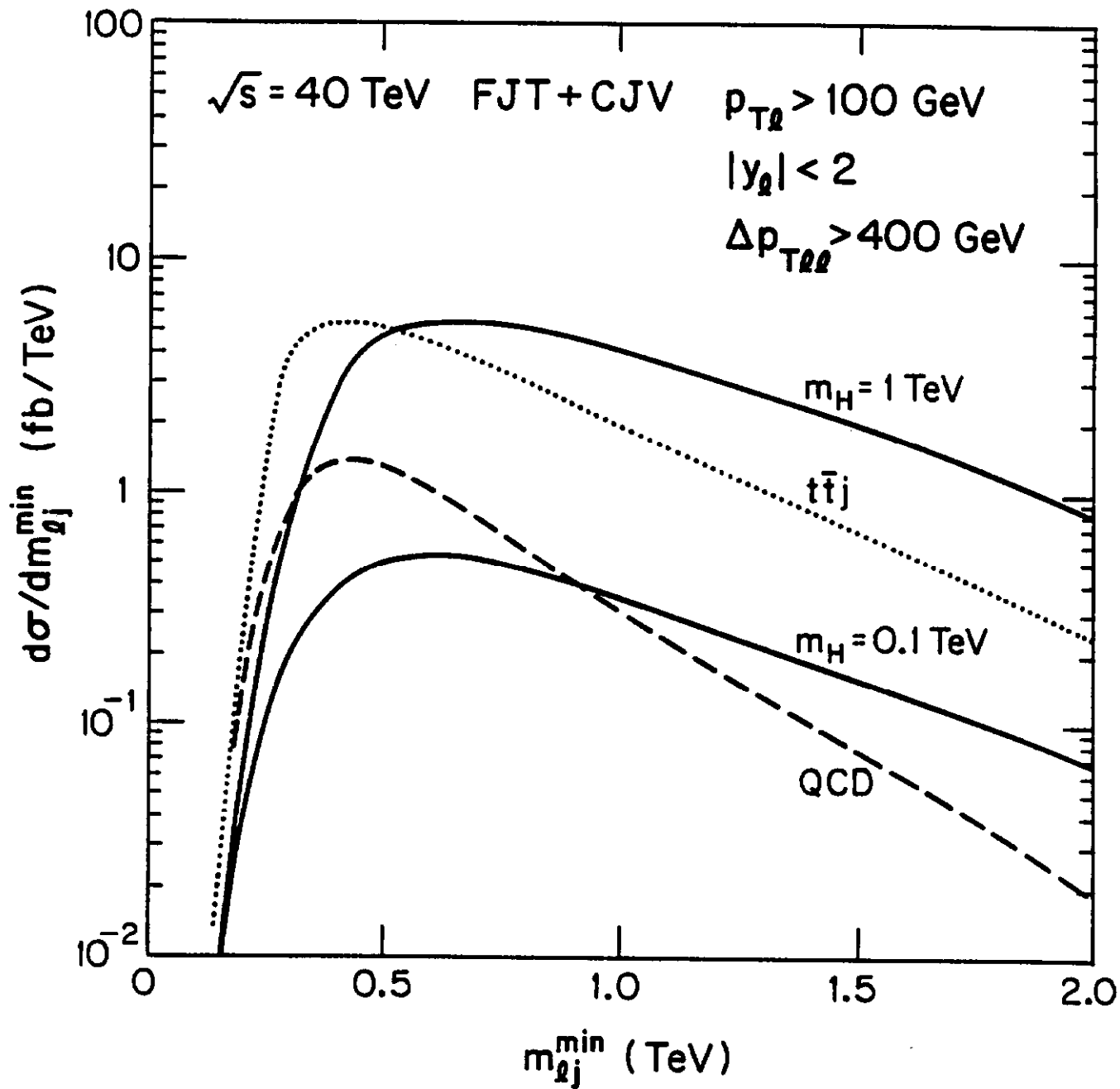


Figure 6